fw

3997

Fabrication of glass photonic crystal fibers with a die-cast process: comments on the reported fiber attenuations in the visible regime

Xian Feng, Wei H. Loh, and David J. Richardson

Optoelectronics Research Centre, University of Southampton

Highfield, Southampton, United Kingdom, SO17 1BJ

E-mail: xif@orc.soton.ac.uk

We comment on the recent paper by Zhou, Hou, Li, and Hou [Appl. Opt. 45, 4433-4436 (2006)], in which transmission losses of 0.2-0.3dB/m were claimed across the wavelength range between 420-900nm in a high-index (n_d=1.80518 at 587.6nm) SF6 glass based photonic crystal fiber from a novel die-cast technique. If confirmed, these losses are at least one order of magnitude lower than previous reported losses of SF6 photonic crystal fibers from other fabrication approaches. Here we present a statistic survey on the relationship between the refractive index and the bulk material attenuation, based on a large number of commercial Schott optical glasses with the n_d ranging between 1.40 and 2.05. It shows that the loss of a high-index (n_d=1.80) glass optical fiber should be at the levels of 10-50dB/m at 420nm and 1-10dB/m at 500nm respectively. Moreover, the material attenuation of such a high-index glass fiber should intrinsically show a large decay from 10-50dB/m at 420nm to the level of 1dB/m at 700nm, which is arising from the tail on the ultraviolet absorption edge of the high-index glass extending to the visible

region. Therefore, we conclude that: (1) the low loss of 0.2-0.3 dB/m reported in the commented paper is abnormally one or two magnitudes lower than the material attenuation that a high-index (n_d=1.80) glass optical fiber should have in the range between 420-500nm; (2) the flat loss curve between 420-700nm in the commented paper largely deviates from the intrinsic behavior of a high-index (n_d=1.80) glass fiber.

OCIS codes: 060.2300, 160.2750.

In a recent paper [1], Zhou et al presented a high-index soft-glass (Schott SF6) index-guided photonic crystal fiber (PCF), also known as the holey fiber (HF), fabricated from a novel die-cast method. And a flat loss curve with 0.2-0.3dB/m losses in the wavelengths of 420-900nm was given in [1]. In the past few years, we and other researchers worked on the holey fibers based on the same glass, using different fabrication approaches such as capillary-stacking technique [2] and extrusion technique [3] respectively. A few dB/m of attenuation in near-infrared regime were measured [2, 3]. This is near one order of magnitude higher than the values reported in [1]. One would argue that this large difference could be because a very different fabrication approach was employed in [1]. Starting from the unarguable fact that any index-guided glass fiber should not have the attenuation significantly lower than its bulk material attenuation limit, we presented here with a statistic survey on the bulk attenuation of a large number of optical glasses with various refractive indices. We conclude that, for a high-index ($n_d \geq 1.80$) glass fiber, the reported loss value in [1] is at least one order of magnitude below the bulk material attenuation limit from 420nm to 500nm. Besides the abnormal low loss values, the flatness of the measured loss curve in the commented paper also does not fit the intrinsic decaying behavior of a high-index ($n_d \geq 1.80$) glass fiber in the visible region (400-700nm).

In general, the UV transmittance edge (the short wavelength edge) of a dielectric material like a glass is arising from the electron transition across the optical bandgap. For the outer-shell electrons with stronger confinement, the electron transition can occur only when the electrons absorb photon with higher energy. This means that the UV edge shifts towards shorter wavelengths for a glass consisting of constituent chemical ions with stronger chemical bondings. On the other hand, the high linear refractive index of a glass is due to the high polarizability (and/or the high hyperpolarizability) of the constituent chemical ions. Since the high polarizability of the constituent chemical ions means the weak confinement to the outer-shell electrons of the ions, the UV-edge of a higher index glass consequently shifts towards the longer wavelengths. This is why a high-index optical glass normally appears colorful and a high-index glass optical fiber typically has high attenuations in the visible regime.

For the conventional index-guided optical fibers, the total fiber attenuations will always be more or less higher than the material attenuation, because of the formation of the imperfections inside the fiber structure during the fiber fabrication. This is also true for a holey fiber based on index-guiding mechanism. Thus it is a very useful way to predict the ultimate fiber attenuation from the bulk material attenuation. To evaluate the bulk optical glass as the good candidate of the low-loss fiber material, four main classic methods were developed ~40 years ago [4] to measure the total attenuation of the bulk glass: (A) transmission comparison method [5], (B) unclad fiber method [6], (C) calorimetric method [7], and (D) two-beam method [8]. All these four methods have been proved that they are reliable experimental methods for measuring bulk material attenuation.

Using the transmission comparison method, we investigated the bulk attenuation at 420 and 500nm of 107 types of commercial Schott optical glasses, including all 105 types of Schott glasses currently available in [9] and Schott SF58 and SF59 available in [10]. For each type of glass, the internal transmittances from 250nm to 2500nm with the thicknesses of 10mm and 25mm are provided in [9, 10]. Using the definition of the attenuation, $loss(dB/m) = -\frac{10}{\Delta l} \cdot \log_{10}(\frac{T_{25mm}}{T_{10mm}})$, where Δl is the thickness difference between two samples (in meter) and T is the transmittance at a single wavelength respectively, the bulk losses of all these 107 types of glasses were calculated from 400 to 700nm. In Fig.1, we show the relationship between the bulk attenuation (at 420nm and 520nm) and the refractive index n_d (at 587.6nm, the d line of helium) of the investigated glasses. It is seen that the bulk attenuations at 500 and 420nm both increase with the linear refractive index n_d. At the short wavelength of 420nm, the slope of such an increase with the index is much higher than that at 500nm.

We then chose another method, the unclad-fiber method developed by Kaiser [6], in order to check the validity of the statistic results in Fig.1. Schott SF59, SF58, SF57, SF6, and F2 glasses with the n_d between 1.62-1.95 were investigated. A rod with 14mm diameter and ~100mm length was core-drilled from each type of bulk glass and then drawn into the unclad fiber with the uniform 250μm outer diameter. Using the cutback method, the loss spectrum of each unclad fiber was measured from 600nm to 1750nm. The fabrication procedure and the loss measurement for the fiber have been described in details somewhere else [11]. The loss spectra of the unclad SF59, SF58 and SF6 glass fiber are illustrated in Fig.2. Note that SF59, SF58 and SF6 glasses have the n_ds of 1.95250, 1.91761 and 1.80518, respectively. In order to minimize the external influences such as the fiber facet quality etc, all the cutback measurements were repeated for 3-4 times totally and each cutback length was between 1-2 meters. The total cutback lengths are 2.50m, 6.55m, and 7.20m for the measured SF59, SF58, and SF6 unclad fibers respectively. Therefore, it can be affirmed that the enhancement of light intensity after the cutback is dominantly attributed to the decrease of the fiber length. From Fig.2, it can be seen that the attenuations of these three unclad glass fibers and their bulk attenuations from the transmission comparison method are overlapped reasonably well in the range between 600-700nm with ~2dB/m deviation.

When measuring an optical glass with very low loss, all the above four classical methods have their own limitation on the accuracy [4]. For the transmission comparison method, the difference of the surface losses between the thick sample and the thin sample will cause large deviation for the results. Moreover, for measuring the low attenuation like 1dB/km in the glass, which corresponds to a transmission difference of 10^{-4} for two samples with the thickness difference of 0.4m, two glass samples with very large thickness difference are required. But it is normally difficult to prepare the sample with the large thickness such as tens of centimeters. For the unclad fiber method, although it can ultimately achieve 2dB/km accuracy for the level of 10dB/km attenuation [6], extremely high cleanliness of the fiber surface is required since the light is guided at a long distance by total internal reflection.

In our this work, with only 15mm thickness difference and 0.1% transmittance of accuracy from the spectrometer, the ultimate accuracy of the transmission comparison method is ~0.3dB/m. In addition to the uncertainty from the surface scattering from the samples with different thicknesses, its actual accuracy is estimated to be 1dB/m. The unclad fiber method here has the estimated accuracy of 0.2dB/m because the cutback length of 1-2meters was used. This is the main reason why there is ~2dB/m deviation between these two methods in the range of 600-700nm (see Fig.2). However, for a material with a high loss at 10-100dB/m level, the material attenuation is dominant in the measurement and the above external factors affecting the accuracy all become negligible. For all the glasses with the n_ds higher than 1.80, ±1dB/m accuracy from the transmission comparison method is reasonably reliable compared to the attenuation of 10-100dB/m from 420-500nm.

In summary, for an index-guided optical fiber based on a high-index glass with the n_d of 1.80 like SF6 glass, (1) the reasonable fiber attenuation should be 10-50dB/m at 420nm and 1-10dB/m at 500nm; (2) in the whole visible regime (400-700nm), there intrinsically exists a decay of the bulk material attenuation, dropping dramatically from tens of dB/m at 400nm to the level of 1dB/m at 700nm by at least one order of magnitude. All the works on high-index glass HFs [2, 3, 11, 12] strongly support these two intrinsic characteristics of high-index glass fiber. Thus, we conclude that, (1) the loss values of 0.2±0.05 dB/m in the whole visible range reported in the commented paper are one to two orders of magnitudes lower than the material attenuation of the high-index SF6 (n_d=1.80) glass; (2) the flatness of the loss curve in the commented paper (see Fig.7 in [1]) does not match the intrinsic attenuation behavior of a high-index (n_d≥1.80) glass fiber in the visible regime. In fact, only a low-index (n_d≤1.6) glass fiber can have such a low-loss and flat curve in the visible regime. We would expect that the authors of the commented paper explain such a large deviation from our statistic results based on the large number of experimental data.

References

1. G. Zhou, Z. Hou, S. Li, and L. Hou, "Fabrication of glass photonic crystal fibers with a die-cast process," Appl. Opt. **45**, 4433-4436 (2006).

2. X. Feng, A.K. Mairaj, D.W. Hewak, and T.M. Monro, "Towards high-index-glass based monomode holey fibre with large-mode-area," Electron. Lett. **40**, 167-169 (2004).

3. V.V.R.K. Kumar, A.K. George, W.H. Reeves, J.C. Knight, P.St.J. Russell, F.G. Omenetto, and A.J. Taylor, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation," Opt. Express, **10**, 1520-1525 (2002).

4. W. Heitmann, "Attenuation measurement in low-loss optical glass by polarized radiation," Appl. Opt. **14**, 3047-3052 (1975).

5. K.C. Kao, and T.W. Davies, "Spectrophotometric studies of ultra low loss optical material I: single-method," J. Sci. Instrum. (J. Phys. E), **2**(1), 1063-1068 (1968).

6. P. Kaiser, "Spectral losses of unclad fibers made from high-grade vitreous silica," Appl. Phys. Lett., **23**, 45-46 (1973).

7. D.A. Pinnow, and T.C. Rich, "Development of a calorimetric method for making precision optical absorption measurements," Appl. Opt. **12**, 984-992 (1973).

8. A.R. Tynes, A.D. Pearson, and D.L. Bisbee, "Loss Mechanisms and Measurements in Clad Glass Fibers and Bulk Glass," J. Opt. Soc. Am. **61**, 143-153 (1971).

9. Schott E-Catalogue 2000-Optical Glass for WINDOWS Ver. 1.1E (2001).

10. Schott E-Catalog Optical Glass: Schott'96 for WINDOWS (1996).

11. X. Feng, A.K. Mairaj, D.W. Hewak, and T.M. Monro, "Nonsilica Glasses for Holey Fibers," J. Light. Tech. **23**(6), 2046-2054 (2005).

12. J.Y.Y. Leong, P. Petropoulos, J.H.V. Price, H. Ebendorff-Heidepriem, S. Asimakis, R.C. Moore, K.E. Frampton, V. Finazzi, X. Feng, T.M. Monro, and D.J. Richardson, "High-Nonlinearity Dispersion-Shifted Lead-Silicate Holey Fibers for Efficient 1-μm Pumped Supercontinuum Generation," J. Light. Tech. **24**, 183-190 (2006).

Figure captions

Fig.1 Relationship between bulk attenuations (upper: at 500nm; lower: at 420nm) and the linear refractive index n_d of 107 types of Schott optical glasses

Fig.2 Comparison of attenuations of unclad fibers and bulk attenuations of high-index Schott SF59, SF58 and SF6 glasses

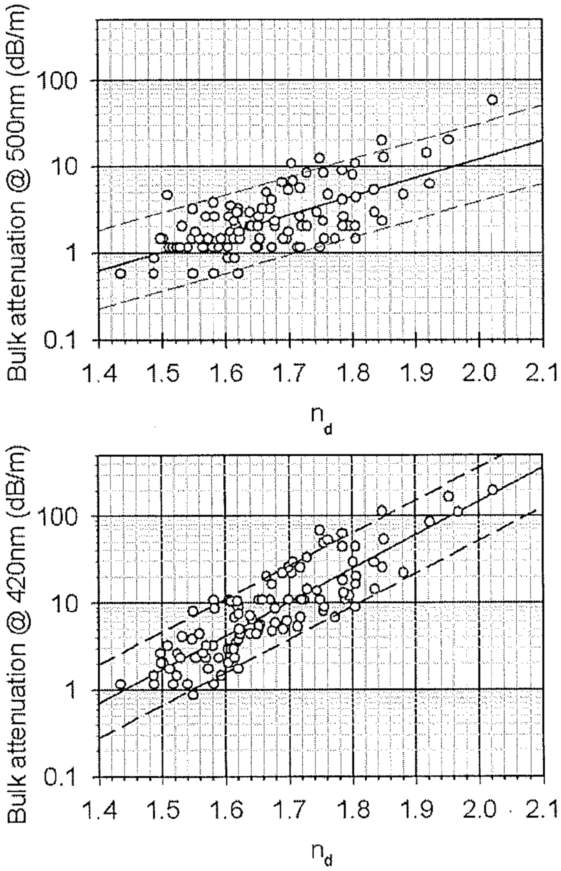

Fig. 1 by Xian Feng, et al.

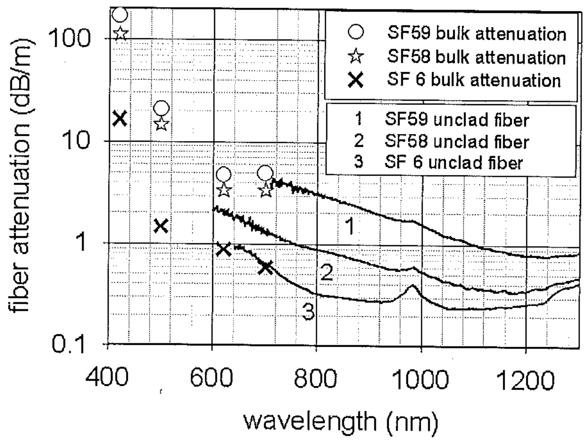

Fig. 2 by Xian Feng, et al.